The Use of System Dynamics Simulation in Integrated Water Resources Management

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Abstract

In this paper we discuss the use of system dynamics as a methodology with which to address dynamically complex problems in water resources management. Problems in regional planning and river basin management, urban water management, flooding and irrigation exhibit important short-term and long-term effects, and are often contentious issues with high potential for conflict. We argue that system dynamics combined with stakeholder involvement provides an appropriate methodology to address these issues effectively. We trace the theoretical and practical evolution of system dynamics in these areas over the past 40 years. From this review of the literature we identify and discuss a number of best practices and common pitfalls in applications of system dynamics.

1 Introduction

Widespread recognition of the impact of human activities upon natural systems is transforming the way we view and manage the earth's resources. The quest for sustainable management of the earth's resources in the light of multiple bottom line considerations has significantly broadened the focus and goals of management endeavours and is one of the most demanding challenges facing society today (Chaves and Alipaz, 2007; European Union; World Water Assessment Program, 2006).

Readily available water resources have already been extensively exploited across much of the planet, and development pressures, population growth and climate change place additional stresses upon this vital resource (Baron et al., 2002; Gleick, 2000; Jackson et al., 2001). Increasingly, we are forced to consider approaches to utilization of remaining marginal water sources, though such measures can be delayed and potentially avoided by placing appropriate emphasis upon the demand rather than the supply side of the water balance equation. In many parts of the world, significant and highly contested discussions are underway regarding future management of water resources, placing increasing emphasis upon water trading and pricing (Howe et al., 1986; Islam et al., 2007; Luo et al., 2007).

Traditional 'command and control' approaches to water resources management emphasized concerns for the provision of adequate water resources to meet human needs, without giving due regard to the maintenance of ecosystem services (Holling and Meffe, 1996). We already live with the legacy of past actions, especially those associated with high-cost engineering infrastructure. Increasing efforts are being made to redress the environmental impacts of these measures, in programmes that target the maintenance or replacement of water supply infrastructure, dam/weir removal, 'naturalisation' of artificial channels, etc. One thing is abundantly clear, technical advancements, in themselves, will not engender sustainable outcomes (Higgs, 2003). Sustainable practice requires a shift in outlook towards application of proactive measures that 'work with nature'. In striving to meet societal needs while maximizing the life-supporting capacity of the planet, an ecosystem approach to natural resources management emphasizes concerns for the resilience of living, vibrant river systems, recognizing explicitly the diversity, complexity, variability and uncertainty of natural systems (Everard and Powell, 2002).

As legislative and policy frameworks adjust to these altered and evolving circumstances, personnel with responsibilities to implement these transitions in practice face significant challenges in the identification, development and application of appropriate management methods, e.g. Brierley and Cullum (in Review); Rogers (2006). The broader range of faces and opinions at the decision-making table highlight concerns for differing perspectives and approaches to sustainability, balancing concerns for development and environmental/cultural protection. Critically, these concerns are expressed using widely differing forms of information and insight, whether qualitative or quantitative, scientific or spiritual. New tools are required to integrate this breadth of perspectives in endeavours to scope the future. These efforts must target the key issues of concern, the critical stressors that affect the viability of sustained resource supply and environmental health, and identify the vital priorities that can be meaningfully addressed in a strategic and proactive manner.

Foresighting exercises provide an informed basis for proactive management strategies, enhancing our prospects to maximise the adaptive capacity of the system as a whole. Dynamic simulation techniques provide a flexible tool with which to perform these analyses. Effective approaches to the generation and use of these modelling tools enhance our capacity to extrapolate and interpolate in a meaningful manner, framing system-specific applications in a broader context. Such exercises present an opportunity to test our understanding, exploring its implications and contradictions by raising and interrogating hypotheses.

In this critical review of the literature, we appraise the suitability of systems dynamics methodology as a tool for integrative resource management by tracing theoretical developments and applications for the past 50 years. We discuss success factors and potential pitfalls of reviewed work, and highlight prospects for future applications of system dynamics methodology to approach the sustainability agenda in a genuine and substantive manner. We then consider factors that hinder the uptake of systems dynamics methodology, prompting resistance to more widespread applications.

2 Dynamic simulation in water resources management

2.1 The uses of dynamic simulation

Due to the complex nature of the problems addressed in water management, the use of dynamic simulation models has a long tradition (Rogers and Fiering, 1986). Models are representations of a complex reality – a theory of how the world operates at some level of aggregation. Models are used to test theories, to explore their implications and contradictions. We constantly form mental models as we perceive and make sense of the world around us (Doyle and Ford, 1998). Mathematical models are a more deliberate act of representing the problem we are concerned with in a scientific form. Their usefulness lies in the fact that they allow us to test real world behaviour in an artificial setting, thus being easy and inexpensive to perform in repetition. With ever increasing computer power we are able to deal with increasingly large and complex data sets.

Dynamic simulation allows us to observe the behaviour of a modelled system and its response to interventions over time. Dynamic simulation models consist of equations describing dynamic change. If system state conditions are known at one point in time, the system state at the next point in time can be computed. Repeating this process one can move through time step-by-step over any desired interval. Simulation aids our capacity to make predictions of future states. As long as the model describes reality with a certain accuracy, the modelling process and its outcomes can be used to improve our understanding of the problem as a necessary step towards affecting sustainable and effective change.

2.2 System dynamics methodology

Numerous analytical procedures have been developed to perform dynamic simulation. It is beyond the scope of this paper to review these comprehensively. Rather we briefly contrast statistical forecasting with system dynamics, and then concentrate on the latter for the remainder of this paper.

In statistical forecasting models equations are developed *ex post*, i.e. following observation, such that the model output matches available historical data as closely as possible. This is usually done through regression analysis. The equations are subsequently used to calculate future model states, i.e. the simulation of future states is based on historical data. As there is no guarantee that these statistical correlations truly forecast future system behaviour, measures of error are introduced to quantify uncertainty.

In contrast, system dynamics models are *causal* mathematical models (Barlas, 1996). In system dynamics methodology (SDM) the underlying premise is that the structure of a system gives rise to its observable and thus predictable behaviour (Forrester, 1968, 1987). The first step in any system dynamics modelling project is to determine the system structure consisting of positive and negative relationships between variables, feedback loops, system archetypes, and delays (Sterman, 2000; Wolstenholme, 2004). This is followed by *ex ante* projection where future system states are replicated from this model.

The difference between *ex post* forecasting and *ex ante* projection implies that uncertainties with regards to future changes in system structure can be more easily addressed as there is better understanding of system structure in the first place (Sterman, 1994). This understanding of system structure requires a focus on the system as a whole and we argue that holistic system understanding is a necessary condition for effective learning and management of complex systems as well as consensus building. These are important goals in their own right. Additionally, systems modelling and simulation supports policy analysis and evaluation (Morecroft, 1992).

SDM consists of qualitative/conceptual and quantitative/numerical modelling methods (Dolado, 1992). Qualitative modelling, e.g. using causal loop diagrams (Figure 1) or hexagons (Hodgson, 1992), improves our conceptual system understanding. Quantitative modelling, e.g. using stock-and-flow models (Figure 2), allows us to investigate and visualise the effects of different intervention strategies through simulation. Quantitative modelling also requires us to make explicit statements about assumptions underlying the model, identify uncertainties with regards to system structure, and identify gaps in data availability. This promotes model transparency.

An SDM project consists of the following phases: problem definition, system conceptualisation, model formulation, model evaluation/testing, policy analysis and implementation (Richardson and Pugh III, 1981; Roberts et al., 1983; Sterman, 2000). These phases are pursued in an iterative fashion (Homer, 1996). Commonly listed purposes for the development of SD mod-

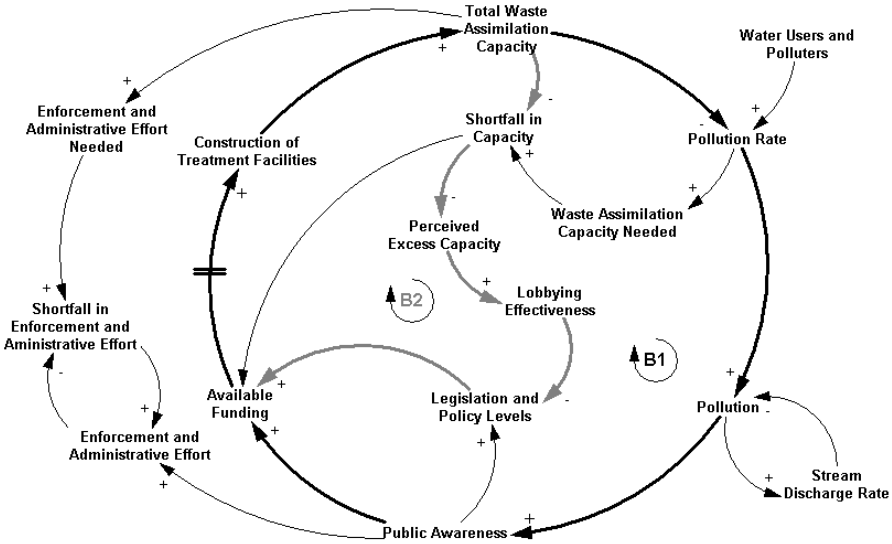

Figure 1: *Causal Loop Diagram describing water quality dynamics. Arcs describe the directions of influence. A positive arcs reads as "an increase in variable A leads to an increase in variable B". A negative arc reads as "an increase in variable A leads to a decrease in variable B". Two feedback loops are highlighted: B1 (thick dark arrows) explains how an increase in water pollution over time leads to an increase in water treatment. Due to system delays (double line), this balancing loop is likely to result in oscillating pollution levels over time. B2 (thick light arrows) shows how lobbyists (polluters) utilise the existing waste assimilation capacity to affect a change in public policy to their advantage. The interaction between B1 and B2 gives rise to complex system behaviour.*

els are improved system understanding, the development of a tool to analyse and evaluate strategies and policies, and the testing of theories (Barlas and Carpenter, 1990; Richardson and Pugh III, 1981; Sterman, 2000).

SDM explicitly asks for user input during the modelling process (Rouwette and Vennix, 2006; Vennix, 1996) and is thus well suited for stakeholder participation. Modelling and simulation are aimed at providing valuable insights into the problem structure instead of giving precise answers. They are thus suited to investigate dynamically complex processes that have important short- and long-term effects. Further advantages of system dynamics methodology have here been categorised under three broad headings (flexibility, ease of uptake and adaptability, ongoing testing and learning) and are summarised in Table 1.

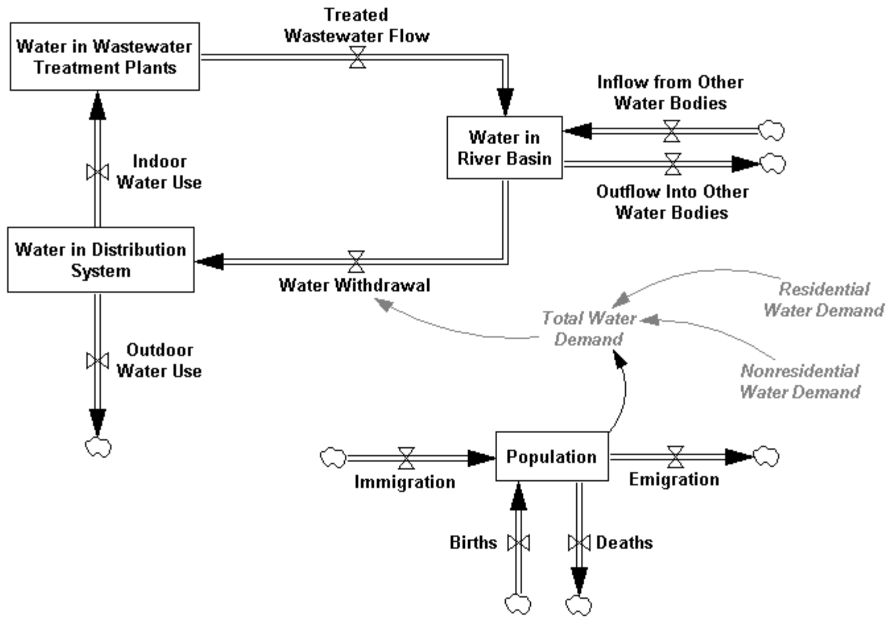

Figure 2: *Stock-and-flow diagram describing an urban water system. Boxed variables represent stocks, double arrows represent flows that increase or decrease stock levels. Auxiliary variables (italics) can influence any other component. The simulation showed, among other things, how outdoor water use has a more adverse effect on water resources than indoor water demand. Adapted from Stave (2003).*

Category	**Explanation**
Flexibility – can be used for a wide range of applications and supports working with multiple bottom line dimensions	Supports the use of qualitative and quantitative variables in models: relationships between variables can be defined on an ordinary scale, e.g. low, medium, high, as often used in modelling social system components. Cross-scalar: a nested scale of models can be developed Modular object-oriented nature of models: models often consist of different sub-models (or modules) increasing interchangeability and reusability. Supports a variety of project goals: the focus of any project can be on the model development process itself to support consensus building and team learning, the final model and its use in simulating system behaviour under different scenarios, or both.

Established methodology, ease of uptake and adaptability	The dynamic nature of the model and its transparency allows users to quickly become familiar with modelling and simulation as they are encouraged to alter the model structure, parameters and data on their own, and explore model capabilities and outcomes. Computer software (e.g. Vensim®, Stella™, Powersim, Simile) is widely available and significantly reduces the cost of programming and running the model. Compilation and simulation is fast. There is a wide variety of model outputs including tables, graphs and diagrams, wide range of sensitivity analysis capabilities, and in-built error checking capabilities (Eberlein, 1989). Parameters do not necessarily need to be fixed before simulation. They can be either manually or dynamically adjusted.
Foresighting, ongoing testing and learning, stakeholder participation	Simulation allows for the continuous testing of assumptions and sensitivity analysis of parameters, with few restrictions on problem presentation so long as variables can be identified and relationships defined (Morecroft, 1988). No simplification is required to make the model mathematically tractable and no objective function needs to be specified. Methods are available to support consensus building and team learning throughout the different stages of the model development process (Vennix, 1996).

Table 1: *Overview of key strengths of system dynamics methodology.*

From our point of view, the key factor influencing the acceptance and success of models is their practical usefulness. A model is useful when it serves the purpose for which it was developed: it addresses the right problem at the right scale and scope, and it represents system response correctly. While the former refers to a model's breadth and depth, the latter addresses model validity. Models are an abstract representation of our limited understanding of reality and reality in an open system can never be fully defined. Hence, the concept of validity is flawed and models are never valid (Oreskes et al., 1994; Sterman, 2002). The challenge becomes to find more appropriate measures of model quality. Model usefulness and quality are subjective concepts which do not lend themselves easily to a definition of objective measures. Moreover, the greater the level of uncertainty and complexity of the problem, the more superficial objective quality measures become. As a result, model validation becomes a social process where model structure and outcome is negotiated until judged valid and useful by all involved parties (Barlas and Carpenter, 1990). This concept of model usefulness requires transparency of the model development process and the model itself. In contrast to system dynamics models, standard black box models do not provide this level of transparency, but often require expert knowledge in order to understand and use them. Although this may increase confidence in the model in the short term, any dependence on experts will decrease model usefulness either because of the expense and time required or because of the model's lack of adaptability to new parameters, questions, and concerns.

Model developers and users can gain confidence in system dynamics models through testing (Barlas, 1989, 1996). Three classes of tests are suggested: structure tests, behaviour tests and policy implication tests. *Structure tests* determine how well the structure of the model matches the structure of reality. This is the case when every model component has a real world counterpart and when every key factor contributing to the problem in the real world has a model counterpart. As descriptions of system structure are generally not available, they have to be extracted from the mental models of people familiar with the system. However, system understanding of different actors is usually not identical. One goal of participative modelling may thus be to increase the degree to which overlap occurs, i.e. build consensus. Furthermore, key factors contributing to the problem may be unrecognised prior to modelling and there is no guarantee that they will be discovered during the model development process. *Behaviour tests* determine how consistently model outputs match real world behaviour. This can either be based on available time-series data or the correlation of mental models with established reference modes (Sterman, 2000). The usefulness of the former clearly depends on the quality of the available historical data, while the latter necessitates a substantive and coherent overlap in mental models. *Policy implication tests* determine whether the observed system responses to policy changes replicate model predictions. These tests are rarely conducted as they take place after implementation when the development team's involvement has usually ceased. This underlines the need for a transparent model developed in collaboration with the end user. Statistical tests are commonly not conducted with system dynamics models as the focus is on the interplay between all model components and model behaviour rather than certain parts of it.

Operations research type models are able to provide exact, optimal solutions because of the way in which problems are articulated, focussing upon one-dimensional engineering-based approaches to water supply performed with little regard for social, cultural and environmental values/implications (Gleick, 2000). Inevitably, the limited regard for social dimensions, sustainability or biodiversity management is now demanding a shift in perspective (Hjorth and Bagheri, 2006). Increased recognition and acceptance of complexity and uncertainty has promoted increased use of flexible simulation based tools, such as those provided by SDM applications (Sterman, 2002; Vriens and Achterbergh, 2006).

Water resource managers need to be aware of a number of limitations of system dynamics before considering its use. Inherent uncertainties of complex open systems implicate that SDM will not provide exact solutions and answers. It is thus not suited to address well-defined operational problems. Concerns for model depth may be evident, reflecting the level of aggregation. Clearly, in light of existing uncertainty, a detailed system description is pointless. The level of detail should mirror the problem description and be effective in addressing the problem in its entirety while striving to be parsimonious to aid model transparency and ease of understanding (Saeed, 1992). The quantification of qualitative variables may be challenging but qualitative data collection and analysis techniques may be utilised (Luna-Reyes and Andersen, 2003). Indeed, differences in value judgements can dramatically influence which policies are ultimately recommended (Andersen and Rohrbaugh, 1992). Furthermore, the definition of the problem boundary, i.e. the model breadth, can be problematic. Modellers are advised to be parsimonious and only include variables if they contribute to generating the problem behaviour as experienced in reality (Sterman, 2000). This highlights the fact that system dynamics modelling is more of an art than a science. Providing rigour in the light of complexity and uncertainty indeed seems to be the main challenge of this approach. The likelihood that two individuals will develop the same system dynamics model given a complex problem statement is small (Ansoff and Slevin, 1968).

Given its flexibility and transparency, and increasing recognition of the complex, multi-dimensional nature of water resource management issues, SDM provides valuable tools for analysing complex interdisciplinary problems that inherit uncertainty, aiding efforts at foresighting and guiding decision-making. Key factors that have assisted these developments have been the capacity to integrate qualitative and quantitative information, the ability to integrate a wide range of input parameters in a meaningful way (reflecting their inherent interactions and feedbacks), explicit recognition of multiple forms of uncertainty, and recognition that the direction of change is the key parameter to effectively guide management programs and responses in an adaptive fashion.

3 Evolving use of system dynamics methodology in water resources management

Over the last 40 years, system dynamics applications in WRM have branched off in many directions. We categorise these by their main problem foci: regional analysis and river basin planning, urban water, flooding, irrigation and pure process models (Figure 3). For an overview of general dynamic water resources management models the reader is referred to Fleming (1975), Donigian (1981), Troendle (1985), El-Kadi (1989), DeVries and Hromadka (1993), Singh (1995) and particularly Wurbs (1994). Only Wurbs (1994) contains a section on modelling using the object oriented (system dynamics) Stella™ modelling environment and one reference of its application.

The development of system dynamics models to analyse problems and identify solutions for improved water resources management has a long tradition. The Stanford Watershed Model (Crawford and Linsley, 1966) is commonly credited as being the first comprehensive watershed simulation model, developed shortly after the emergence of SDM (Forrester, 1958). However, while the Stanford Watershed Model was a hydrological response process model aimed at simulating physical water flows and stores, the first system dynamics models included physical as well as socio-economic factors in order to improve understanding of long-term systemic issues faced in the region. The Susquehanna River Basin Model developed by Hamilton during the 1960's and published in book form in 1969 aimed to understand the interdependencies between water resources and their management on the one hand and quantifiable social and economic factors (demographics, employment, industry) on the other (Hamilton, 1969). This additional model complexity, while visionary at the time given available computer capabilities, came at the cost of increased data aggregation and larger spatial scale.

The use of system dynamics for integrated regional analysis has continued to this day. While spatial scales have shifted from regional (Camara et al., 1986; Cartwright and Connor, 2003; Cohen and Neale, 2006; Connor et al., 2004; Den Exter, 2004; Den Exter and Specht, 2003; Guo et al., 2001; Leal Neto et al., 2006; Passell et al., 2003; Sehlke and Jacobson, 2005; Xu, 2001; Xu et al., 2002) to national (Simonovic and Fahmy, 1999; Simonovic and Rajasekaram, 2004) to global (Simonovic, 2002a,b), so too have the number of socio-economic factors included, mirroring improved computer capabilities as well as changing problem foci (global water crisis and social impacts). Simonovic and Rajasekaram (2004) note a recent trend in the reduction of spatial scales to basin and watersheds in order to identify regional and local solutions.

Applications in regional analysis have often had a strong economic focus examining feedback relationships between industry and available water resources. River basin and watershed management applications focus more narrowly on water resources and their interaction with population growth (Costanza and Ruth, 1998; Ford, 1996; Gastelum Perez, 2006; Huerta, 2004; Leal Neto et al., 2006; Peterson et al., 2004; Sander et al., 2000; Tidwell et al., 2004; Van den Belt, 2004). As with regional analysis tools, temporal scales of these models are typically long-term (50–100 years).

Urban water resources management may be seen as a special case of watershed management where concerns are more immediate and more contentious. This typically increases model complexity challenging the model development process (Bagheri, 2006; Bagheri and Hjorth, 2007; Grigg, 1997; Passell, 2004; Stave, 2002; Wallace et al., 1988). Furthermore, spatial boundaries for water resources management are harder to establish due to the intricate nature of water transfers from the far hinterland.

During the 1990's, SDM projects increasingly incorporated participatory methods, particularly in the areas of regional analysis, and regional and urban watershed management. This reflects increasing demands for stakeholder involvement and public-centered decision making in environmental resource management. Critically, SDM has the flexibility and capability to support deliberative-analytical processes effectively.

Further recent research foci have been the management of flooding (Ahmad and Simonovic, 2000, 2001, 2004, 2006; Li and Simonovich, 2002) and irrigation (Diaz-Ibarra, 2004; Fernandez and Selma, 2004; Saysel, 2004; Saysel et al., 2002). In these areas, models increasingly aim to investigate spatial outcomes (Ahmad and Simonovic, 2004) and operational planning over shorter temporal scales.

Pure SDM process models are rare, for examples see Vezjak et al. (1998) and Abbott and Stanley (1999), with restricted spatial and temporal scales. This reflects the limited use and acceptance of SDM for well-defined and detailed problems. Although few applications are evident, use of SDM to assess water quality dynamics are also noteworthy (Albuquerque, 2001; Fasset and Rostapshov, 2001; Hines and Knight, 1971). The flexibility of this methodology is also reflected in the analysis of institutional processes in water resources management (Gates et al., 1970; Males and Gates, 1971).

From the outset, system dynamics applications aimed to integrate various physical, social and economic factors influencing water resources management with a view to addressing and planning for intra- and inter-sectoral long-term problems. Indeed, system dynamics appears to be the methodology of choice for these multidisciplinary and multi-actor problems. Consequently, temporal scales of these models need to be long-term to be able to reflect system delays.

However, despite many applications in the 1960's and 1970's uptake of SDM subsequently stalled. Initial acceptance of these type of applications was low and few projects made it to publication. Models were often highly aggregated and thus did not address the day-to-day operational concerns of municipal water managers (for example Grigg and Bryson (1975); Hamilton (1969)). Moreover, the *zeitgeist* of the time was that everything seemed to be analysable and solvable, so that complexity and uncertainty could be disregarded (Ackoff, 1993, 1974). The strength of operations research type models to provide exact, optimal solutions for these type of problems and likely the negative publicity and misunderstanding at the time surrounding the "Urban Dynamics" (Forrester, 1969) and "Limits to Growth" (Meadows et al., 1972) studies may have lead to a growing apprehension towards SDM that can still be felt today (Lane, 2000; Sharp and Price, 1984). Interestingly, underlying concepts of the systems approach became entrenched in the *systems approach* to water resources management (Biswas, 1976; Grigg, 1977). Grigg defines this systems approach as "a systematic method to conceptualize the water resources 'system' and use the tools of systems analysis (databases, models,

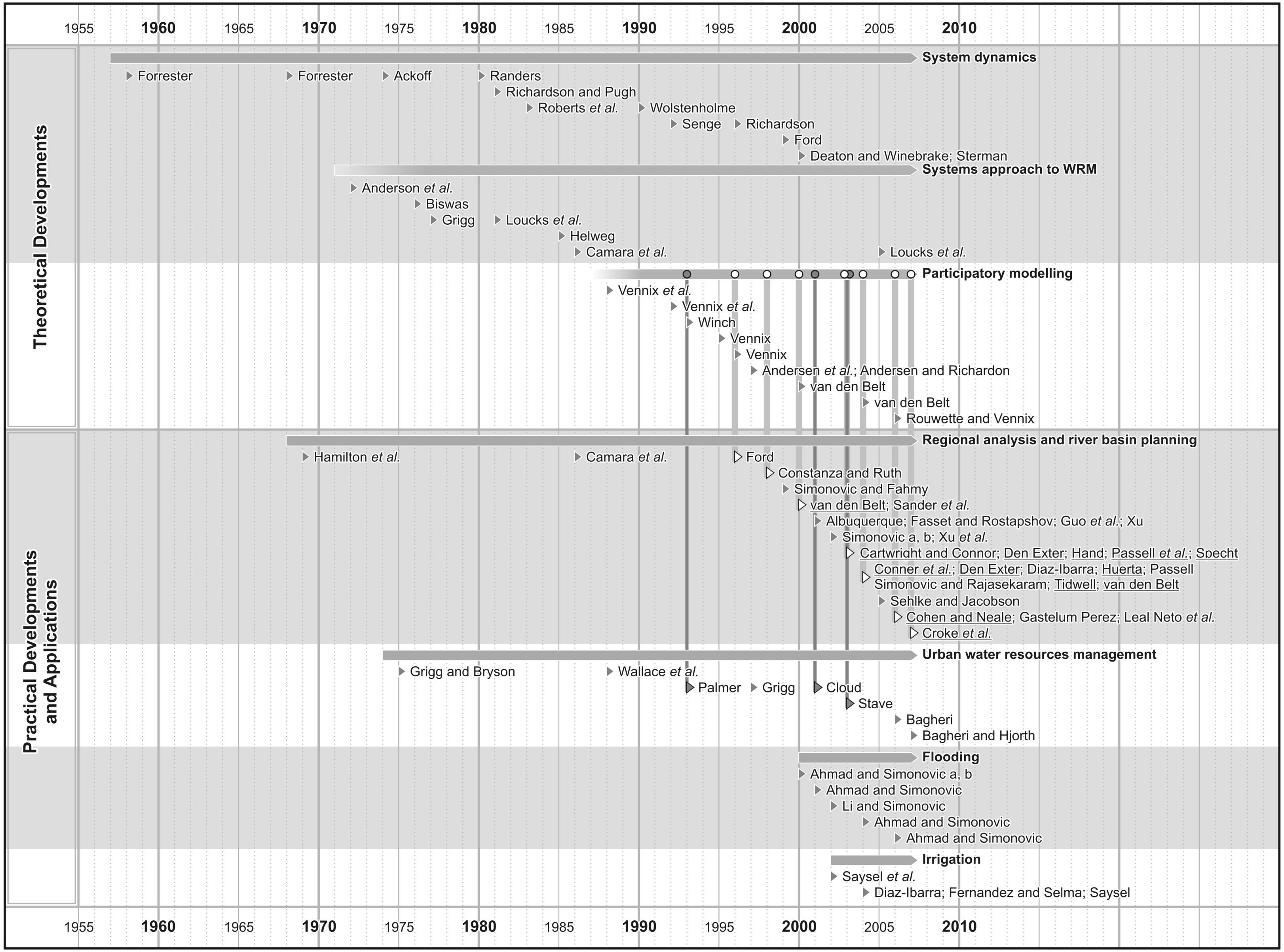

Figure 3: *A timeline of key theoretical and practical research output. Downward arrows indicate which applications utilised participatory methods.*

GIS) to identify and evaluate management strategies" (Grigg, 1997). These applications supported the emergence of *Integrated Water Resources Management* in the late 1980's (Bowden and Glennie, 1986; Da Cunha, 1989; Rogers, 1993). Integrated water resources management not only acknowledges the integrative nature of water resource problems but also the need to incorporate multiple objectives and involve multiple stakeholders in decision making.

During the 1990's SDM applications became more varied. Models either increased in complexity to make them more useful in operational planning (c.f. work by Simonovic) and provide expert knowledge in areas such as power generation, flooding and reservoir control, or models increased in simplicity and became even more aggregated in order to support learning and problem understanding (c.f. work by Ford (1996); many other applications not published). Models aimed at strategic planning and policy making persisted, but over the last ten years participatory methods have taken a strong hold. Requests for participative adaptive management were increasingly voiced and legislation, such as the European Water Directive, now prioritises stakeholder participation in water management (European Union).

While many initial applications have their origins in the United States, recent years have seen a global spread with particular uptake in Europe. The three trends of using system dynamics methodology for operational planning, learning support and participatory strategic planning are expected to persist.

4 Discussion

Reviewed work illustrates that careful problem definition and project focus are paramount for a successful project. To a certain degree this is a necessary condition for any modelling project. However, SDM enables more leeway in setting model breadth and depth, and thus requires that more attention is paid to these details at the outset. Similar findings are reported by Eskinasi and Fokkema (2006), who indicate that the lack of project definition and model scope in application of a SDM project ultimately lead to its downfall.

SDM provides the unique opportunity to model and test long-term effects of management decisions and strategies in uncertain and complex systems while facilitating stakeholder involvement and supporting consensus building. A focus on these strengths should persist throughout any project to avoid the modeller or end-user becoming bogged down in details of model structure or statistical validity. This requires that the selected level of aggregation corresponds well with the problem of interest and the data available. For example, Stave (2003) illustrates that a model does not have to be complex in order to be useful and achieve desired outcomes.

Where outcomes have not been achieved, for example see Grigg (1997) this was notably due to lack of careful initial scoping which often takes place independently from the anticipated end-users.

Stakeholder involvement in any SDM project can vary to a great extent.

Stakeholders can be fully engaged in the model development process itself, contribute by suggesting strategies, experiment with a complete model, or simply provide feedback in an information session. It is considered advantageous that use of SDM does not require any knowledge of the methodology, modelling or computer simulation, such that this approach can be used with any group of stakeholders. The degree to which stakeholders are involved will to some extent contribute to the success of the project and as a result should be carefully considered. If stakeholders are expected to take ownership of the model/decision support tool, they have to be included in problem definition and project scoping processes at the outset.

In contrast to other dynamic simulation approaches, SDM is based on a better understanding of system structure. However, this does not make simulation results any more valid and care must be taken not to oversell the methodology. To date, major applications lie in regional analysis and river basin planning, urban water management, flooding and irrigation. Resistance to a wider uptake manifests from misconceptions regarding the purpose and value of systems models, historical animosities with system dynamics, the notion that SDM is "just another method", the relative unfamiliarity of SDM outside North-America and Europe, the notorious lack of time of many managers to engage in conceptual broad-picture thinking, as well as the complexities and problems surrounding implementation of systemic solutions.

Drawing on our review of the literature, we summarise common pitfalls and criteria of successful SDM projects in Table 2.

Success criteria	**Common pitfalls**
Careful problem definition, scoping of project aims and model boundaries	Insufficient definition of the problem, project purpose and deliverables; Institutional arrangements, boundaries and organizational politics that limit uptake are not addressed at the outset (Eden et al., 1979); Misunderstanding or misjudging the purpose and value of conceptual or systems modelling and simulation
Conceptual and numerical models of high quality, i.e. models that are parsimonious and able to communicate well the system structure and dynamic behaviour pertaining to the problem at hand	Extending model boundaries during modelling; A focus on modelling a system rather than modelling a problem leading to overly complex models that are difficult to understand for non-experts

Models that are tested to the extent that end users and/or stakeholders are confident in the simulation results	Models that are based on individual untested mental models
Stakeholder participation to the extent that it supports defined project goals	Independent model building that does not lead to insights and may appear obscure to end users and/or stakeholders; Misjudging the conflict potential among stakeholders and a lack of processes that support consensus building; Underrating the impact of individual differences in value judgements by stakeholders; Targeting and selecting stakeholders in order to evade conflict
A focus on personal and institutional learning and change	Expectations of exact predictions; Overrating short-term system effects over longer term effects
Support for implementation of results at the outset	Lack of top-management support for the implementation of short-term or long-term solutions, and their monitoring
Models that can be revised and updated in order to support adaptive project management	Overly complex models that are not based on modules making revision and extension difficult

Table 2: *Common pitfalls and success criteria observed during literature review.*

Numerous research gaps are well suited for system dynamics modelling: water quality management especially the assessment of spatial effects of land use change and non-point source pollution; the interconnections of the four different types of water in urban vs. rural areas; the analysis of institutional decision processes and stakeholder dynamics; modelling in support of multiple bottom line reporting as well as virtual water trading dynamics.

5 Conclusions

New agenda items of sustainability, multiple bottom lines, stakeholder participation and the efficient management of scarce and contested water resources pose significant challenges for resource planners and managers. Dynamic simulation methodologies such as system dynamics programming have been suggested and applied to address these issues and scope the future. Despite various limitations, system dynamics is well suited for multidisciplinary and multi-actor problems but not operational problems in integrated water resources management.

However, the value of such procedures is limited if outcomes are not believed or uptake of outcomes is not forthcoming. SDM provides tools with considerable flexibility with which to approach foresighting exercises. However, findings from this review indicate that prospects for success are maximised when the group itself constrains the definition of the problems to be addressed, and participatory procedures are applied in scoping, development and testing of the model. Involvement underpins ownership, providing the platform for management applications that are not only responsive to group concerns, but also have greater prospects for effective implementation and uptake.

SDM offers prospects to enhance the resilience of the system as a whole. It provides a well-grounded, flexible and realistic approach to identifying and dealing with inherent uncertainties in water resources management. Hence, it prospectively provides a critical tool in adaptive management applications, assisting in derivation and ownership of realistic visions for integrated water resources management, and the development of strategies that must be adopted to achieve these goals. Given the openness and transparency of participatory processes, SDM also provides an opportunity to meaningfully test projections of system futures and the reliability/deficiencies in our understanding. In light of these insights, we are able to progressively adapt management strategies to changing circumstances. Such flexibility is vital in responding to prevailing development pressures, climate change and measures that deal with the long term consequences of our past “command-and-control” legacies. In addition, application of SDM procedures provides opportunities to monitor performance indicators and enhance effectiveness in our quest to manage water effectively and sustainably.

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